Comprehensive Investigation of Nonlinear Site Response: Collaborative Research with UC San Diego and UC Davis

January 1999 through October 1999

USGS Award No.: 99-HQGR-0020

Ahmed Elgamal and Tao Lai
Department of Structural Engineering, University of California at San Diego
La Jolla, California 92093-0085

Tel: 858-822-1075
Fax: 858-822-2260
E-mail: elgamal@ucsd.edu
URL: http://www-mae.ucsd.edu/research/elgamal

Program Element: II

Key Words: Amplification, Geotechnical Site Effects, Engineering Seismology

Non-technical Summary

The objective of this research is to conduct highly accurate and highly instrumented, physical model tests to study the nonlinear behavior of stiff soil sites during earthquakes. Results of this testing program will establish guidelines as to when nonlinear site response analyses are called for, and when linear or equivalent-linear analyses can predict near-surface accelerations with sufficient accuracy. For this purpose, the centrifuge testing technique is employed to thoroughly document the seismic response of a dense compacted sand stratum. The wealth of documented accelerations (surface and downhole) are utilized within a system identification framework in order to fully characterize the damping and stiffness characteristics of stiff soil sites. Appropriate computational models for prediction of seismic site response will be proposed and calibrated, along with the identified dynamic soil properties.

Investigations Undertaken

Two centrifuge experiments have been conducted at the University of California at Davis (UCD), using very dense sand as the soil material. These experiments were highly instrumented and the recorded extensive data are contained in two reports (tests DKS02 and DKS03, Stevens *et al.* 1999a&b, or see the UCD web-site http://cgm.engr.ucdavis.edu/download/data/dks/). In the first experiment (test DKS02), shaking was imparted at centrifugal accelerations of 10*g*, 20*g* and 40*g*, representing prototype sites of 5.5*m*, 11*m* and 22*m* depth respectively. In our initial phase of analytical investigations, the 22*m* depth soil profile is being thoroughly studied within a shear-beam model and system-identification framework. The shear beam model is chosen because of its simplicity as well as its applicability for situations of highly nonlinear response. System identification (Zeghal 1990) is employed to define the values of the two most influential but unknown parameters (i.e., shear wave velocity profile and viscous damping) that provide a best match to the experimental dynamic soil response, at ground surface and all downhole accelerometer locations.

In all, eight earthquake events are studied in the current phase of investigation. Table 1 lists the shaking (earthquake) event designation, peak ground acceleration (PGA) and event strength category (in the order reported by UCD, Stevens *et al.* 1999a). Roughly, the shaking events were divided into the three categories of "very small", "small", and "moderate" shaking events as judged by the peak ground acceleration at ground surface (Table 1).

No.	Event	Surface PGA, *g*	Event Category
1	DKS02_u	0.051	Very Small
2	DKS02_v	0.052	Very Small
3	DKS02_bk	0.117	Very Small
4	DKS02_bl	0.277	Small
5	DKS02_bt	0.411	Moderate
6	DKS02_bu	0.431	Moderate
7	DKS02_bv	0.196	Small
8	DKS02_by	0.413	Moderate

Table 1: Shaking Events at a Centrifugal Acceleration of 40*g* during Test DKS02

A pattern recognition analysis was first performed using the acceleration recordings, in order to define the site amplification characteristics, fundamental resonant frequencies and evidence of nonlinear effects. The analysis included studies of acceleration Response Spectrum, Fourier Spectrum and input-output Transfer Functions.

System identification was then applied to calibrate the dynamic parameters of the employed shear beam code. The identified properties are found to be consistent among the events considered, and show good agreement with laboratory experiments (Arulmoli *et al.* 1992) and with our collaborators' independent investigations (Kutter *et al.* 1999) as shown below.

Results

The identified dynamic soil properties are shown in Figures 1 and 2. The shear wave velocity profiles are shown together with other experimental results by Arulmoli *et al.* (1992) and Kutter *et al.* (1999). It is noted that shear wave velocity decreases and damping increases with the increase in earthquake acceleration amplitude (consistent with the characteristics of shear modulus reduction and increased damping with the increase in shear strain for sand). The results reported in Figures 1 and 2 draw attention to the following points:

1) Shear wave velocity profiles depict the expected dependence on vertical confinement for a cohesionless soil.
2) These velocity profiles show a reduction of 10% - 15% for the very small shaking events compared to the results suggested by Kutter *et al.* (1999) based on a conducted air-hammer test.
3) During the moderate shaking events (PGA of about 0.4*g* in Table 1), the shear velocity profile shows an additional 10% reduction due to nonlinear effects.

for a best fit of the very small shaking events (PGA of 0.05g – 0.1g). In addition, the small and moderate shaking events (PGA of 0.2g – 0.4g) required a lower bound damping of at least 8.5% (Figure 2).

The above strongly suggests a response (frequency-independent and strain-dependent) similar to that of computer models such as SHAKE91 (Idriss and Sun 1991). In fact, SHAKE91 is currently being prepared for use in this project.

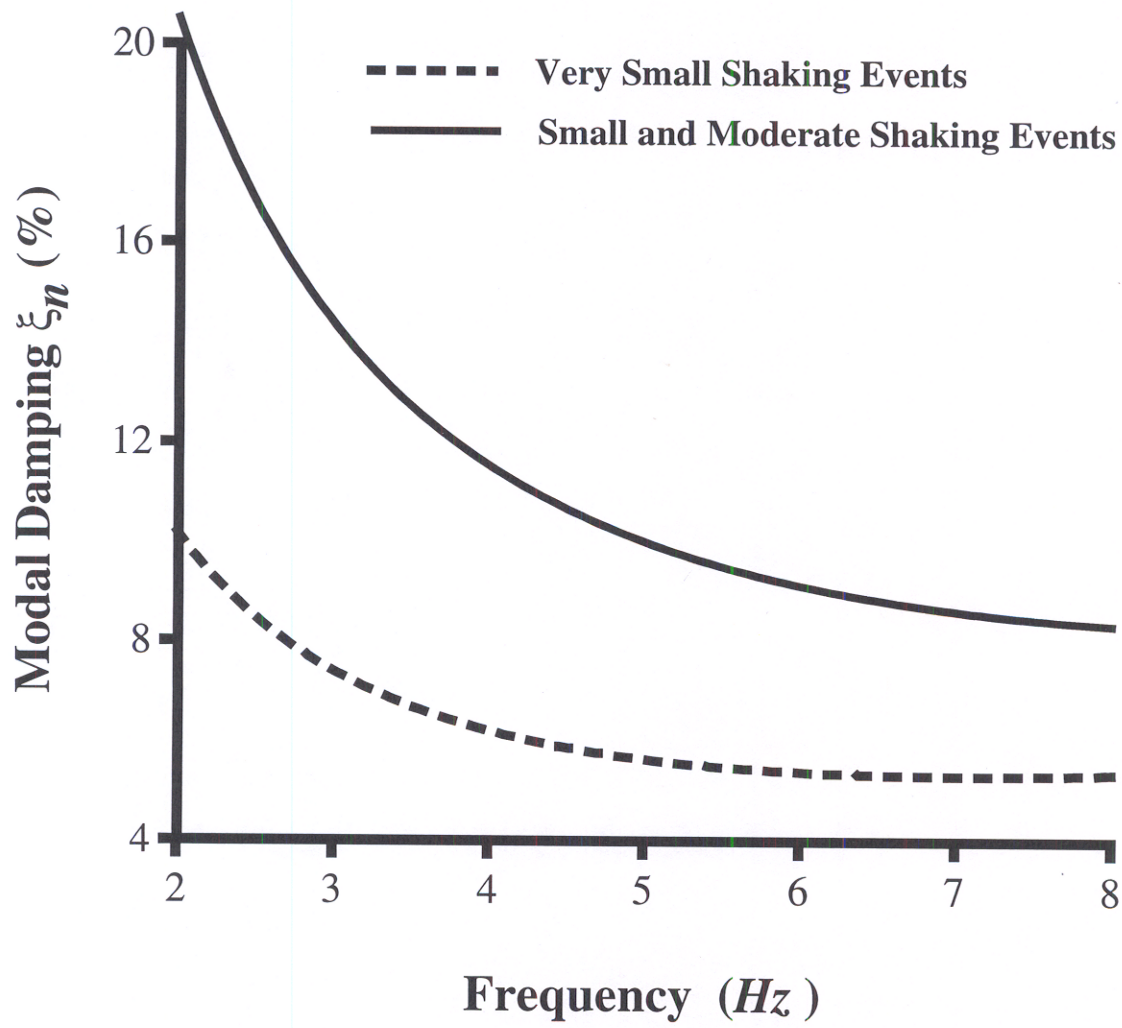

Figure 2: Identified Viscous Modal Damping

Using the identified soil properties (Figures 1 and 2), the site responses were computed for all eight shaking events of Table 1 (Tao and Elgamal 1999). A comparison of recorded and computed responses (event DKS02_bl) at two locations is shown in Figures 3 and 4. This comparison shows the effectiveness of the shear beam model and the worthiness of the employed identification algorithm. Similar results were obtained for the eight investigated shaking events at all accelerometer locations (Tao and Elgamal 1999).

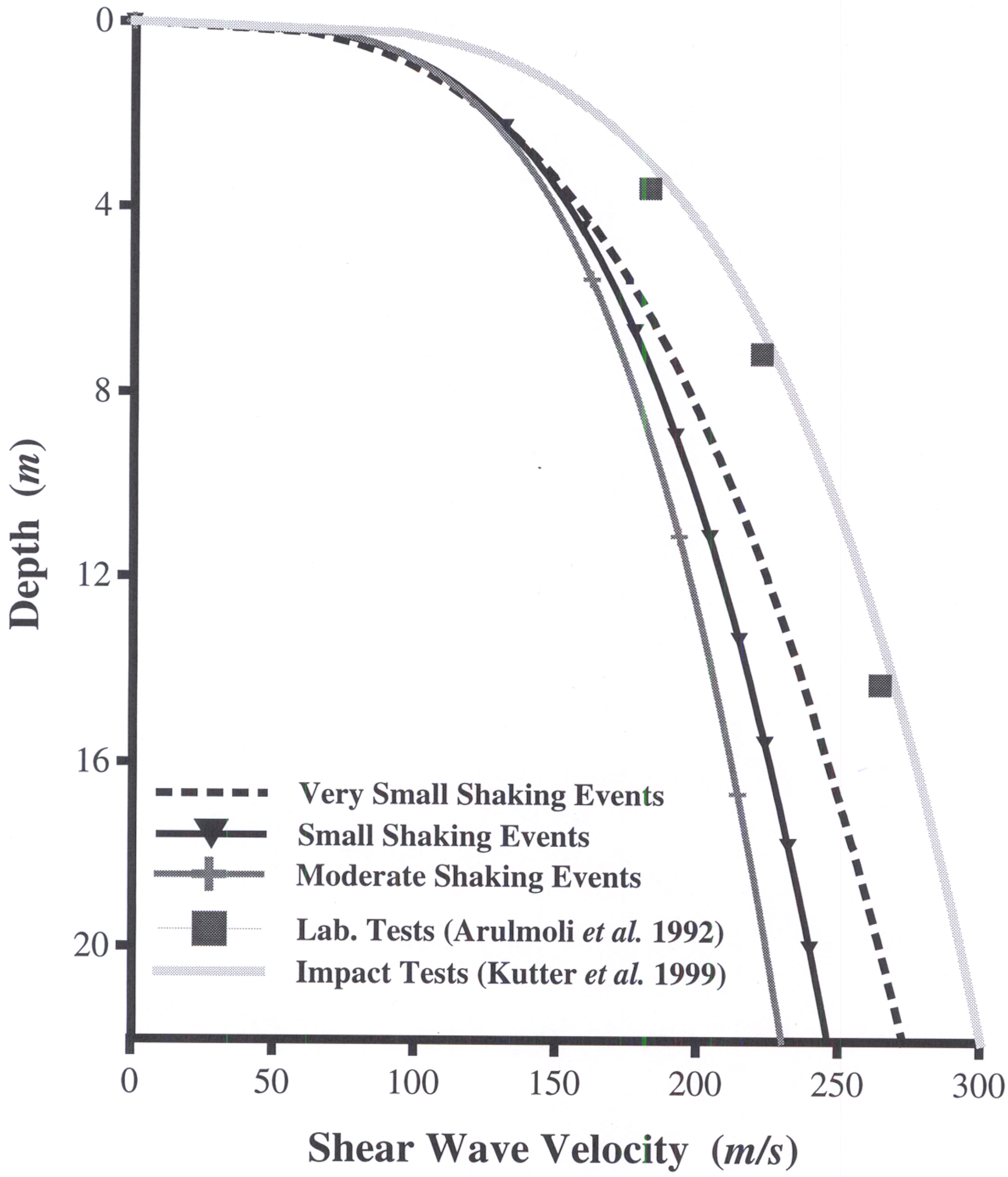

Figure 1: Identified Shear Wave Velocity Profiles

4) Damping is seen to increase with shaking amplitudes (strain-level dependent damping). At frequencies of about 4*Hz* and above, damping is fairly constant (i.e., frequency independent). In fact, the increase in damping below 4*Hz* does not necessarily reflect an actual physical phenomenon, but rather may be a limitation of the employed viscous damping model (of the classical form $\mathbf{C} = a_m\mathbf{M} + a_k\mathbf{K}$, where **C**, **M**, and **K** are viscous damping, mass, and stiffness matrices respectively, and a_m and a_k are user-defined scalar multipliers). However, it may be noted that damping of about 5.5% is needed

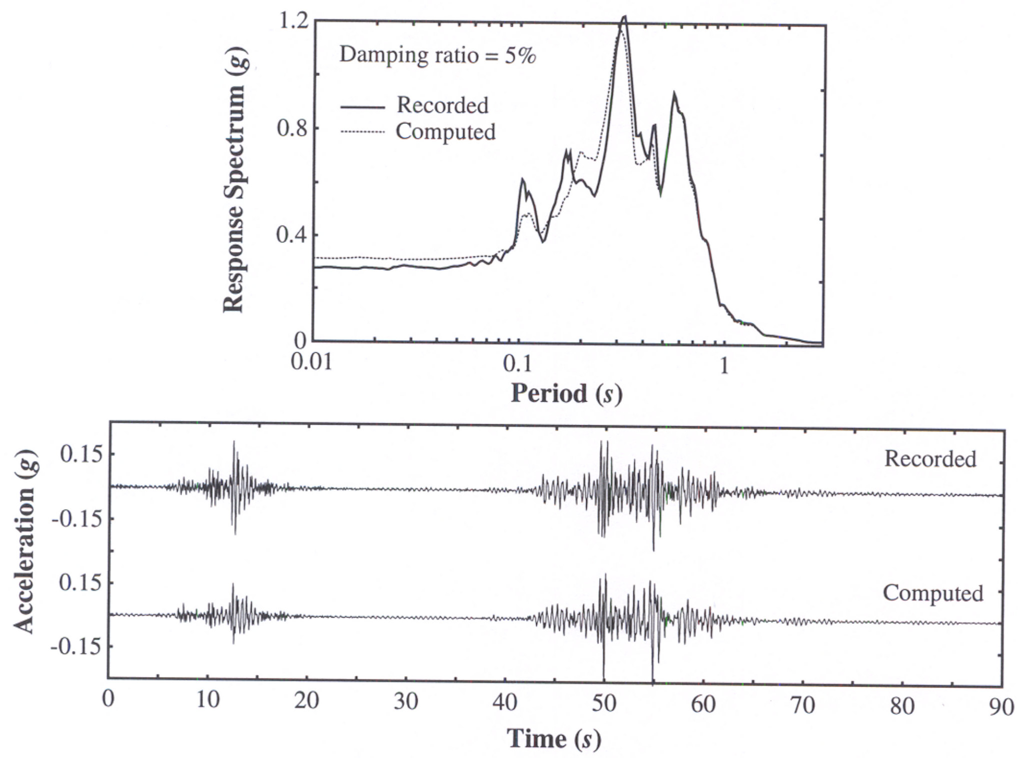

Figure 3: Comparison of Recorded and Computed Response at Ground Surface (DKS02_bl)

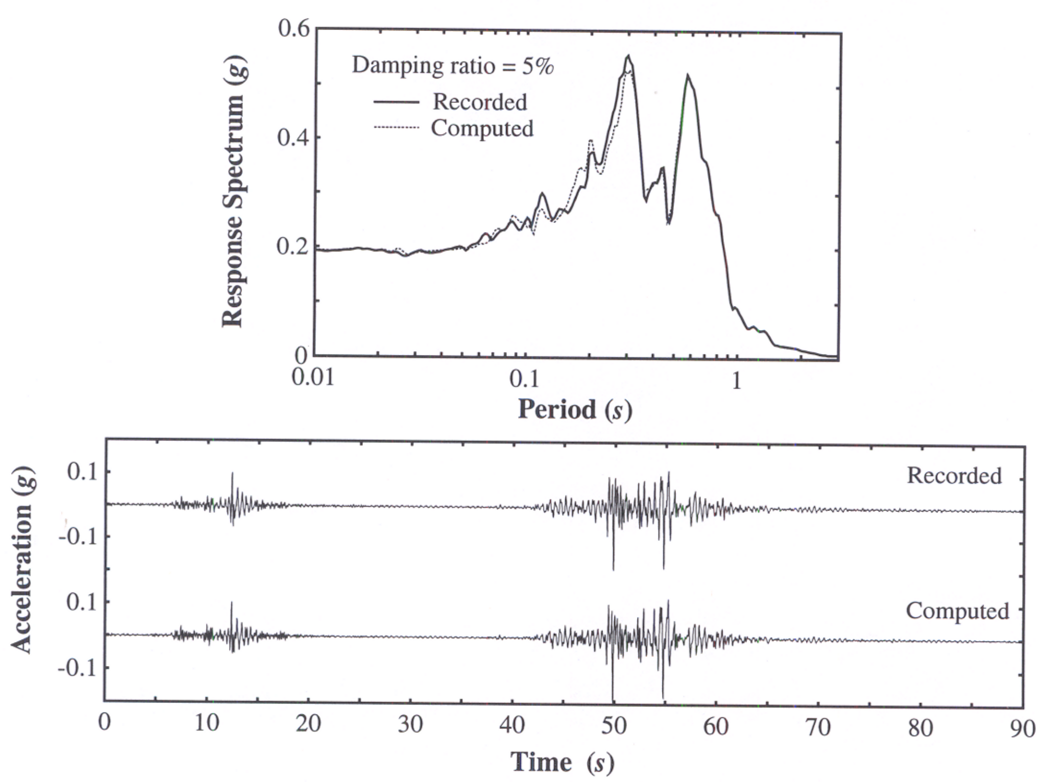

Figure 4: Comparison of Recorded and Computed Response at 19m Depth (DKS02_bl)

Future Work

Ongoing studies will address the following aspects:

1. Adopt SHAKE91 to do site response analysis and system identification because of the observed nature of dynamic soil response at lower shaking amplitudes (frequency independent damping and shear strain-dependent response).
2. Thoroughly investigate the highly nonlinear phases of dynamic response and develop guidelines for modeling and prediction.
3. Include all experimental data for the 5.5*m*, 11*m* and 22*m* site profiles and data of all other centrifuge experiments.
4. Adopt a two-dimensional (2D) model to more accurately represent the centrifuge container and the resulting 2D site effects. The 2D studies will be used to extract more accurate soil properties and will be compared to the values identified from 1D investigations.

References

Arulmoli, K., Muraleetharan, K.K., Hossain, M.M. and Fruth, L.S. (1992), *VELACS – Verification of Liquefaction Analyses by Centrifuge Studies, Laboratory Testing Program Soil Data Report*, Report to National Science Foundation, The Earth Technology Corporation.

Kutter B.L., Wilson, D.W., Stevens, D.K. and Kim, B.I. (1999), *Comprehensive Investigation of Nonlinear Site Response – Collaborative Research with UC San Diego, and UC Davis*, Annual Project Summary to USGS, Dept. of Civil & Environmental Engineering, University of California at Davis.

Idriss, I.M. and Sun, J. (1991), *User's Manual for SHAKE91*, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA

Stevens, D.K., Kim, B.I., Wilson, D.W. and Kutter B.L. (1999a), *Comprehensive Investigation of Nonlinear Site Response – Centrifuge Data Report For the DKS02 Model Test*, UCD/CGMDR-99/02, Dept. of Civil & Environmental Engineering, University of California at Davis.

Stevens, D.K., Wilson, D.W. and Kutter B.L. (1999b), *Comprehensive Investigation of Nonlinear Site Response – Centrifuge Data Report For the DKS03 Model Test*, UCD/CGMDR-99/03, Dept. of Civil & Environmental Engineering, University of California at Davis.

Tao, L. and Elgamal, A. (1999), *Comprehensive Investigation of Nonlinear Site Response – Preliminary System Identification Study of Test DKS02 Data*, Department of Structural Engineering, University of California at San Diego, CA.

Zeghal, M. (1990), *System Identification of the Nonlinear Seismic Response of Earth Dams*, PhD thesis, Princeton University, New Jersey.

Reports Published

Tao, L. and Elgamal, A. (1999), *Comprehensive Investigation of Nonlinear Site Response – Preliminary System Identification Study of Test DKS02 Data*, Department of Structural Engineering, University of California at San Diego, CA.